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SURVEY OF INLET NOISE REDUCTION CONCEPTS FOR GAS
TURBINE ENGINES

By

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April 1976

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SURVEY OF INLET NOISE REDUCTION CONCEPTS FOR GAS
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SUMMARY

This paper contains an overview of advanced concepts for the suppression of noise in the inlets of gas turbine engines. Inlet geometric and operating parameters are presented and design criteria for suppression methods are discussed. Noise suppression concepts are described, and the directions of current research are reviewed. Problem areas requiring further work are indicated. Considered in the paper are well established approaches to inlet noise reduction - namely, acoustic liners and high subsonic Mach number inlets - which are the focus of considerable current research activity. Also, several germinal ideas are considered, including "active" acoustic absorption and water vapor injection. These are in the very early stages of investigation and appear to require substantially more work before they will be serious contenders for practical applications.

INTRODUCTION

Inlet noise is a significant contributor to the total noise signature of commercial jet transport aircraft and must be controlled to achieve community acceptability and to meet current and future federal noise

regulations. The control of inlet noise can be obtained either at the source through proper design of the rotating components so as to minimize the generation of noise or by appropriate modifications within the inlet duct so as to inhibit the radiation of turbomachinery noise from the inlet face. The last decade has witnessed successful efforts by the universities, the government, and private industry to identify, develop, and implement a variety of methods for inlet noise control. An imaginative research effort continues to improve on established methods and to produce new ideas.

The purpose of this paper is to describe various approaches to noise control within the inlet which may have promise for future applications. Included in the discussion are high subsonic Mach number inlets and acoustic liner concepts. Attention is also drawn to the beneficial use of duct geometry, "active" acoustic absorption, water vapor injection, and blade row reflections. Problem areas requiring further research are indicated.

This paper is , thus, a brief summary of a large amount of information contained in the open literature. In order to keep the reference list within bounds, only selected papers published within the last several years have been cited.

GEOMETRIC AND OPERATIONAL CONSIDERATIONS

The subject of this paper is inlet noise suppression: advanced methods, trends of current research, outstanding problems, and future directions. Consequently, an appropriate place to begin the discussion is with a brief review of the characteristics of fan inlet noise since the reduction of this noise is the primary objective of inlet suppression. A schematic example of

a fan noise spectrum that may occur within an inlet is shown in figure 1. Some actual measurements of fan noise in an inlet are reported in reference 1. Superimposed upon a background of broadband noise are pure tones occurring at multiples of the blade passage frequency. Among the more important sources of these tones are the interaction of rotating blades and stationary vanes with upstream generated wakes, atmospheric turbulence and ground vortices, wall boundary layers, and inflow distortion resulting from crosswinds and angle of attack. On occasion combination tones can be observed which occur at the sum of the harmonics of tones from the fan and from other internal rotating machinery. When the relative Mach number into the fan blades becomes supersonic, shock waves created at the blade leading edges spiral down the duct to form "multiple pure tones" (MPTs). The fundamental tone then occurs at the shaft speed and there may be many higher harmonics which create a very ragged sound spectrum. Internal levels of broadband noise on the order of 120 to 130 dB have been measured. Tones may extend 10 to 15 dB above these levels. Overall noise levels near the fan of 150 to 160 dB are not unusual. In this paper, methods of reducing fan noise within the inlet are described. Methods of reducing the noise at the source by modifications to the fan itself are not considered.

Engine Parameters

Figure 2 summarizes the inlet dimensions and operating conditions bearing upon the subject of this paper for two different engine thrust classes. The smaller thrust class exemplifies the JT3D, JT8D, and refan engines. The larger thrust class includes the CF6, RB211, and JT9D engines. These nominal values are very useful reference points to keep in mind when considering

new suppression methods. The length and diameter of the inlet determine the space available for acoustic treatment. In current nacelles the length available for treatment is generally less than one diameter. Moreover, large diameter inlets have low cutoff frequencies. Thus, the sound field generated by the fan has many propagating modes which must be considered in the design of efficient advanced acoustic liners. The inlet Mach number determines the grazing flow velocity over duct liners and indicates the amount of inlet area reduction which must be achieved to choke the flow. The mass flow rate is of concern when one considers injecting additives into the stream. Of course, the fan tip Mach number is an indication of whether or not MPTs are likely to be generated. Noise suppression methods which result in radical departures from the nominal geometries or operating conditions shown in figure 2 may require major redesign of the nacelle or engine. This can be a very costly and time consuming process in which the economic penalties may completely override the noise reduction benefit.

Constraints

Noise control is just one of many considerations which enter into engine design and operation. Some of the constraints which must be met by inlet noise reduction techniques, if they are to make a minimum adverse impact on the propulsion system design and operation, are listed in figure 3. These constraints are not easy to satisfy simultaneously but must be confronted when one considers implementing a new idea. The application of a very efficient suppression concept may not be feasible if it violates these conditions. Thus suppression methods which promise only moderate noise

reduction but are compatible with these constraints have a much better chance of being incorporated into flight systems.

Having recognized some of the practical limitations and constraints, noise suppression in isolation needs to be considered on its own merits. What approaches look promising for inlet noise reduction? What problems have to be solved in order to realize their full potential?

ADVANCE NOISE CONTROL CONCEPTS

Sonic and High Subsonic Flow Inlets

In this section an overview of the status of recent research findings regarding sonic and high subsonic inlets is presented. The primary objective of this research has been to develop the technology that will permit the practical use of these kinds of inlets on gas turbine engines.

Sonic Inlets: Trends for the static acoustic and aerodynamic performance of a typical high subsonic speed inlet are shown in figure 4 which is taken from reference 2. As the throat Mach number increases the noise radiated from the inlet decreases and the total pressure recovery, which is a measure of the aerodynamic performance, is reduced. When the throat Mach number is equal to 1.0 the inlet is choked and the sonic flow at the throat blocks the radiation of the upstream traveling noise. The physical processes at work are uncertain in detail. The interaction of sound with sonic flows is a fundamental problem which needs to be resolved in order to understand the behavior of a sonic inlet. When the inlet is choked the maximum noise reduction occurs

but it is accompanied by severe performance losses at zero forward speed. By operating at throat Mach numbers slightly less than 1.0 one gets less, but still useful amounts of, noise reduction. Correspondingly, the performance losses also decrease. When operated in this range the inlet is referred to as a high subsonic or accelerating inlet.

To fully appreciate the acoustic benefits to be derived by varying the inlet velocity, consider one-third octave band spectra shown in figure 5 which were taken from reference 3. These spectra have been obtained at the same fan tip speed. As indicated in the sketch at the top of the figure, the axial flow Mach number is varied by the movement of the centerbody. The noise below 1000 Hz can be probably attributed to broadband noise generated upstream of the inlet throat. The highest levels of the baseline noise spectra occur at the fundamental blade passing frequency of the fan. It can be seen that as the axial flow velocity is increased there is a steady reduction in the noise at all frequencies above about 1000 Hz. Thus a wide range of noise reductions are possible which are effective across much of the spectrum. The key to controlling the amount of noise reduction is the control of the flow speed through the inlet. Generally, at higher subsonic velocities, the higher the axial velocity the greater the noise reduction. A central problem to be faced and now being studied is how to trade-off between noise reduction and aerodynamic performance.

The degradation of aerodynamic performance observed in static measurements appears to be significantly lessened when the inlet is operated with forward speed. Figure 6 is a plot of aerodynamic and acoustic performance of a high speed inlet taken from reference 4. These data were obtained in a

wind tunnel, with and without forward speed. The $V = 0$, or static curve, is similar to data taken in an anechoic chamber, see reference 3, for example. This curve shows a typical, significant reduction in compressor pressure recovery as noise is reduced by about 32 dB by increasing the inlet Mach number. The curve to the right was obtained from the same compressor but with the wind tunnel airstream at 148 km/hr (80 knots) and at an angle of attack of 0° . The pressure recovery is dramatically improved over the static test. In fact, the pressure recovery remained above 99-percent up to a noise reduction of about 25 dB. Data obtained at the NASA-Lewis Research Center show that favorable pressure recovery with forward speed may continue to be realized at high angles of attack, see reference 5. These encouraging results have stimulated a renewed interest in the possible application of sonic inlets to aircraft engines and moreover, they point up the need for more testing of inlets in the presence of forward speed.

Hybrid Inlets. - In a hybrid inlet both acoustic treatment and high subsonic velocity airflow are combined to reduce noise. By operating at average throat Mach numbers somewhat less than 1.0, the aerodynamic performance penalties associated with the sonic inlet are favorably reduced. The noise reduction achieved as a result of the high subsonic speed airflow is augmented by sound absorption at the acoustically lined walls. These characteristics of the hybrid inlet are indicated in figure 7 which shows acoustic data for an experimental hybrid inlet compared to

a hardwall baseline or high subsonic Mach number inlet. In this case, the baseline inlet was found to produce noise reductions of up to 13 PNdB at an average throat Mach number of 0.8. With the addition of wall and centerbody treatment approximately 5 PNdB of additional noise reduction was obtained throughout the operating range as indicated by the upper curve. The full potential of the hybrid inlet concept remains to be explored. There are several directions for further research using the hybrid inlet concept such as the combined use of acoustic treatment to improve sound attenuation (a topic to be discussed later in the paper), variable inlet geometry to give greater control of the flow, and wind tunnel testing to optimize aerodynamic and acoustic performance in the presence of forward speed.

Refracting Inlets. - A relatively new noise reduction concept termed a "refracting inlet" has been proposed in reference 6. The basic phenomenon to be exploited in this inlet is illustrated in the sketch at the upper left of figure 8. In the experiment depicted, a sound wave traveling upstream in the narrow portion of the duct is seen to be sharply refracted toward the lower wall after passing through the throat. It is believed that this refraction is caused by the velocity gradients present near the throat, particularly near the lower wall. The amount of refraction is a function of sound wave length and flow speed. This experimental result suggests that it may be possible to use controlled refraction of sound waves to reduce inlet noise as shown in

figure 8. By suitably tailoring the gradients in the inlet flow, noise propagating within the inlet could be redirected towards wall acoustic treatment or radiated noise could be directed away from the ground. By directing more sound energy onto a liner the efficiency of acoustic treatment might be significantly enhanced. Research is currently under way to explore more fully the performance and practicality of the refracting inlet concept.

Theoretical Considerations. - A much better understanding of the propagation of sound through high speed air flows is essential to the improved design of high subsonic Mach number inlets. The fundamental ingredients of this difficult theoretical problem are shown in figure 9. The estimated axial Mach number variation along an annular inlet with a centerbody is illustrated at the top of the figure. The flow speed increases in the contraction, reaches a maximum at the throat, ($M = 1$ when the inlet is choked), and then falls off again as the flow diffuses toward the fan face. The form of a generalized, one-dimensional wave equation governing the propagation of sound through such a flow is shown at the bottom of the figure. The unknown function Ψ is the acoustic velocity potential. On the left-hand side of the equation is the convected wave operator with variable coefficients. The right-hand side consists of terms proportional to axial flow gradients as well as non-linear terms. The former are important immediately ahead of and behind the throat where rapid area changes occur; the latter are significant in the throat particularly as the throat mach number approaches unity. Attempts to study this problem under simplified conditions are available in the literature, references 7, 8 and 9. The results show interesting features such as standing

wave patterns in the inlet due to reflections from the throat and an interchange of energy between the sound and flow fields. A number of researchers, including A. H. Nayfeh and J. E. Kaiser (VPI & SU), E. Lumsdaine (U. of Tenn.), A. Hersh (Hersh Acoustical Engineering), M. Myers (Geo. Washington Univ.), and A. Callegari (Courant Institute) are currently attempting solutions of one-dimensional and axisymmetric models of this formidable problem. The results are sure to bring a new level of understanding to the physics of this complex phenomena.

Advanced Liner Concepts

In this section consideration will be given to progress made on advanced duct liner concepts for improving the sound absorption properties of nacelle acoustic treatment. The goals of this work are to broaden the bandwidth of absorption, to improve low-frequency absorption characteristics and to achieve more absorption with less weight and volume of treatment. An extensive review of duct acoustics and duct liner concepts is given in reference 10.

Variable Impedance. - One approach to increasing liner absorption is the variable impedance concept illustrated schematically in figure 10. In its simplest form, segments of liners having different impedances are placed axially along or circumferentially around the inlet. One can conceive of combining these two discrete patterns and smoothing over the abrupt changes in liner properties to produce a continuous variation in impedance. Experience to date shows that the change in impedance breaks up the orderly modal structure found in a uniformly lined duct and redistributes the acoustic

energy beneficially into nonradiating modes. The axially segmented liner has been studied theoretically and experimentally because it is an arrangement which is relatively easy to set up in a laboratory or to treat theoretically. The continuous variation of impedance may emerge as a useful concept when more sophisticated fabrication techniques and design procedures become available.

A comparison of the transmission loss spectra measured in a flow duct for two 2-segment liners and a uniform liner is shown in figure 11. The uniform liner, configuration C, has a 22.5% porosity perforated plate face sheet and a 1.27 cm deep honeycomb backing. Half of each of the 2-segment liners, configurations A & B, are identical to the uniform liner. The other half has the same face-sheet but has a honeycomb backing three times as deep. The air flow and sound propagation are in the same direction with an airflow Mach number of 0.4. Note that the spectra are different for configurations A & B, indicating that the order in which different liner segments are placed in the duct has a significant influence on the transmission loss. Configuration A has better absorption in the mid-frequency range, 1.0 - 3.0 KHz, than the uniform liner, configuration C, but the maximum attenuations are essentially unchanged. Configuration B provides 6 - 8 dB more attenuation and has much better absorptive qualities than either A or C all across the spectrum from 1 to 8 KHz.

Data on three segment liners, obtained using the 12-inch diameter research compressor in Langley's anechoic test facility, are shown in figure 12. By placing various combinations of inserts in the compressor inlet, a parametric study of segmented liner configurations was conducted in cooperation with the General Electric Company. The spectra in the figure are for a hard-wall inlet,

a uniform liner, and one of the better three-segment liners. The uniform and segmented liners were designed for a circumferential mode order of seven which was predicted by Tyler-Sofrin theory to be the major contributor to rotor-stator interaction noise. It can be seen that the three-segment liner produces greater noise reduction than the uniform liner in the low-and mid-frequency range, as would be expected because of the two thicker treatment sections. Moreover, the high-frequency attenuation is maintained with the segmented liner even though a smaller amount of high frequency treatment is present. One of the aims of current research is to expand to higher values the frequency range over which segmented treatment produces significant additional noise reduction.

Data such as those shown in the preceeding two figures suggest that multi-segment liners may be superior to uniform liners and that the concept deserves further careful investigation. Probably the most urgent need at the moment is for well-controlled tests of multisegment and uniform liners optimized and tested for a known noise source in order to get a true comparison of their relative merits. It will take special care to do this statically in view of what is known about the effects of inlet turbulence on turbomachinery noise generation.

Optimal Liners. - Designing an optimal multisegment liner for a particular application requires the selection of the right combination of impedances for a specified number of segments in order to obtain the maximum attenuation. The optimization problem has been studied recently in references 11 to 15. Since two numbers, the resistance and reactance, must be determined for each section,

the number of independent parameters becomes too large to conveniently handle manually for several segments. A flow diagram of a computerized procedure used at Langley for optimizing liners is shown in figure 13. The heart of the procedure is contained in two programs: one for calculating sound propagation along the duct; the other, for systematically selecting impedance combinations to minimize the transmitted or radiated energy. The propagation program accounts for the duct geometry, mean flow field, and liner impedance. The optimization program must determine the direction for increasing energy loss in a parameter space consisting of the unknown resistance and reactance values for each section. The final output of this iterative calculation is a set of impedance values and attenuation which, in a local sense, corresponds to the maximum possible energy loss.

Figure 14 presents the results of some calculations of optimal segmented liners for a circular duct with no mean flow. Each graph is a plot of the optimal attenuation in dB against the frequency parameter ka , where k is the sound wave number and a is the duct radius. An indication of the potential benefits to be obtained with segmentation is shown at the left. These results are taken from reference 11 which also presents calculations of optimal liners for more realistic turbomachinery noise sources. For a plane wave source the theory predicts that the optimal two-segment liner has as much as 20 dB more attenuation in the range $3 \leq ka \leq 5$ than the optimal uniform liner. Above $ka = 5$ the attenuation for the two-segment liner falls rapidly until at about $ka = 8$ and beyond it is essentially the same as for the uniform liner. The attenuations of optimal two-segment liners for two different types of noise sources are shown at the right. The attenuation which can be achieved for the

point source differs from that which can be achieved for a plane wave over much of the range of ka values. Thus, it appears that an optimal liner must be tailored to a specific noise source if the maximum benefits are to be realized. This fact is one impetus for the current interest in measuring the modal content of fan noise within the fan inlet duct.

Impedance Models. - Accurate values of liner impedance are essential to theoretical predictions. Much parametric testing of liner configurations and materials has been carried out and numerous empirical models to predict impedance have been formulated. The guidelines achieved in this manner are useful for specific liners but are no substitute for fundamental understanding of the processes involved in liner-sound-fluid interaction. Progress in this direction has been slow but encouraging. The schematic diagrams in figure 15 show two recently developed theoretical models for predicting the impedance of perforates. The fluid mechanical model of the impedance of an orifice was developed by Rogers and Hersh, reference 16. An unsteady incompressible flow field near the orifice, consisting of a boundary layer on the plate and a jet through the orifice, is matched analytically to an incident sound wave to give a uniformly valid solution applicable in both the near and far fields. The nonlinear behavior of the impedance at high sound pressure levels is also calculated. A central concept in this theory is the "discharge coefficient" which measures the contraction of the jet through the orifice. Mungur's model of liner impedance is essentially acoustical in concept, reference 17. The external shear flow induces a circulating flow in the backing cavity. In response to an incident sound wave the air in the orifice vibrates up and

down like a piston with velocity U_0 . The response of the piston is influenced by the flow in the cavity. In the usual manner one calculates the impedance of the orifice as the ratio of the total force on the piston to the volume velocity through the orifice. The excellent agreement with experiment shown by these authors is encouraging. It is hoped that these two models and the work of Rice, reference 18, will be stepping stones to even more comprehensive impedance models based on firm physical concepts.

Bulk Absorbers. - Bulk liners offer several attractive features for use as duct liners such as: broad bandwidth of absorption, low cost, ease of handling and fabrication, and favorable low frequency absorption characteristics. As shown schematically at the top of figure 16, materials used for bulk liners have a variety of structures including interwoven fibers, layers, as for fiberglass blankets and pressed felts, and cells, which are representative of foams. When a sound wave in free air passes over the liner it induces a sound wave to propagate within the liner. This wave is dissipated by viscous forces as it progresses through the tortuous air passages in the bulk materials. This transfer of energy from the free air into the liner where it is converted into heat is the source of the attenuation. Unfortunately the inhospitable environment within engine ducts disqualifies many of the traditional bulk absorbers for use as nacelle liners. New materials which are more resistant to wicking, erosion, temperature and vibration hold the key to further progress. Several synthetic materials with these desirable properties are beginning to appear on the market. The availability of these new materials may stimulate a resurgence of interest in the application of bulk liners.

Liner Design. - This discussion would not be complete without mention of the many novel liner designs of L. Wirt of the Lockheed-California Company, reference 19. Wirt's inventiveness has produced a number of unique geometrical arrangements which should not be overlooked as candidates for inlet treatment.

Ideas For The Future

In the remainder of this paper methods of inlet noise reduction will be considered which are considerably less well developed than either high subsonic Mach number inlets or acoustic treatment. These germinal ideas are in the early stages of investigation and will require substantially more development before they will be serious contenders for practical application. The noise reduction potential of these methods has been predicted theoretically and, in some instances, observed experimentally. The ideas may be ideal for special purpose applications or perhaps could be used to augment the effectiveness of other methods. The subjects to be discussed are attractive to the scientist in that they provide ample opportunity for innovative basic and applied research.

Modified Duct Geometry. - Several concepts for inlet noise reduction by modifications to the duct geometry are illustrated in figure 17. These ideas are the scarfed inlet, the tapered inlet, and curved inlet ducts. The scarfed inlet has a protruding lower lip which is shaped to provide some shielding of inlet noise below the engine. This concept has undergone preliminary testing at Lewis Research Center. Proper tapering of the inlet will bring

about an increase in cutoff frequency with distance forward of the fan face. Moreover, a reduction in the inlet diameter reduces the radiation impedance. Reductions in multiple pure tone noise in fan engines have been attributed to some of these effects, reference 20. Finally, research on sound propagation in curved duct suggests that at high enough frequencies, the reflections that occur in a bend makes a curved duct a less efficient sound conductor than a straight duct, references 21 and 22. Thus the use of curved ducts, such as the S-shaped duct on the 727 center engine, may have some acoustic benefits.

Active Acoustic Absorption. - The concept of using one set of sound waves to cancel another set of sound waves, sometimes referred to as "active acoustic absorption", has been studied by several researchers in the last few years, references 23 - 27. The work done recently by Ozlac and Harrington of Pennsylvania State University on the in-duct cancellation of circumferential modes will be described here to explain the basic idea. The tests were conducted in the duct propagation facility shown schematically at the top of figure 18. The source array consists of eight of the 16 acoustic drivers in the end of the duct. This array produces a sound field having the amplitude distribution across the duct shown as the solid line in the plot at the bottom of the figure. The other eight drivers - the cancelling array - produce a similar signal. When these two signals are combined, a maximum noise reduction of about 40 dB is achieved. Effective cancellation is not achieved easily, particularly for higher frequencies and for complex source patterns. Sensitive control systems and very precise electronic equipment are needed to achieve considerable noise reduction uniformly throughout the duct even

for single frequency, steady source noises. The practical demonstration of this concept for broadband noise, unsteady source noises, and for multi-modal source content constitutes a formidable challenge. The advantages claimed for active acoustic absorption are the ability to reduce low frequency noise, which is quite difficult by most other means, and the very short length of duct that would be taken up by the necessary hardware.

Water Vapor Injection. - A cloud of small fluid droplets in air attenuates acoustic disturbances by viscous drag, heat transfer, and vapor exchange with the surrounding gas, reference 28. Consequently, as suggested by the sketch to the left in figure 19, a water droplet cloud sprayed into an inlet might reduce fan noise. An example calculation of the attenuation which can be achieved for a plane wave in a duct is shown at the right of the figure. The calculations were made for 1 micron radius droplets constituting 1% of the gas mass in air at ambient temperature. The attenuation due to phase change becomes noticeable at low frequencies and increases to about 3 dB per meter of axial length at frequencies above 1000 Hz. Furthermore, above 1000 Hz this attenuation is augmented by attenuation due to viscous drag between the droplets and the surrounding air. The amount of attenuation which can be achieved can be controlled to some extent by varying the mass of the vapor in the air, the droplet size, and the volatility of the liquid used. The attenuation shown in this example is predicted to nearly double by using slightly smaller droplets of radius 0.7 micron. Using droplets this size in a 200 KN thrust class engine drawing about 500 kg/sec of air during landing approach leads to the prediction that water injection of 5 Kg/sec during

the critical portion of landing approach will result in a 6 - 10 dB reduction in fan noise at frequencies above 1000 Hz. The theory also indicates that the layer of the droplet cloud near the wall is more effective than the portion in the center of the duct. This conclusion suggests the amount of water injection required may be reduced without much loss in attenuation by producing a droplet cloud only around the periphery of the duct.

Blade Row Reflection. - The blade rows present in gas turbine engines may impede the transmission of sound through fan stages. Hence, it is of interest to determine how the blade rows can be positioned to efficiently reflect noise back toward the engine. The theoretically predicted reflection of a discrete tone by a blade row at low frequencies is shown in figure 20 for a non-rotating blade row, reference 29. Whenever the incident plane wave travels parallel to the blades, $\phi_i = 150^\circ$ for this stagger angle, all of the incident energy is transmitted through the blade row. An incidence angle allowing total transmission always occurs at $(90^\circ + \text{stagger angle})$ and is independent of Mach number, blade spacing, and frequency. The transmitted energy drops off as the incidence angle, ϕ_i , decreases and the plane wave travels more nearly parallel to the blade row. Reflection is more effective at high frequencies and is enhanced by higher flow rates. An experimental study has been conducted to verify these predicted reductions, reference 30. The presence of the reflection phenomena has been confirmed and the basic correctness of the theoretically predicted trends has been verified. Noise reductions up to 9 dB attributable to blade row reflection have been measured. Experience to date, reference 31, suggests that spinning modes rotating in a direction

opposed to the rotor rotation are less likely to be transmitted than modes rotating in the same direction. The technique of "tuning" the blade row for noise reduction appears to have promise but additional experimental work is needed to define its limitations and off-design performance.

CONCLUDING REMARKS

This paper has presented an overview of advanced concepts for the suppression of noise within the inlets of gas turbine engines. The status of research on acoustic liners for ducts and high subsonic Mach number inlets has been summarized. Some directions for improving these suppression methods have been pointed out and the outstanding research problems have been delineated. Attention has been called to several ideas which may find practical application in the future.

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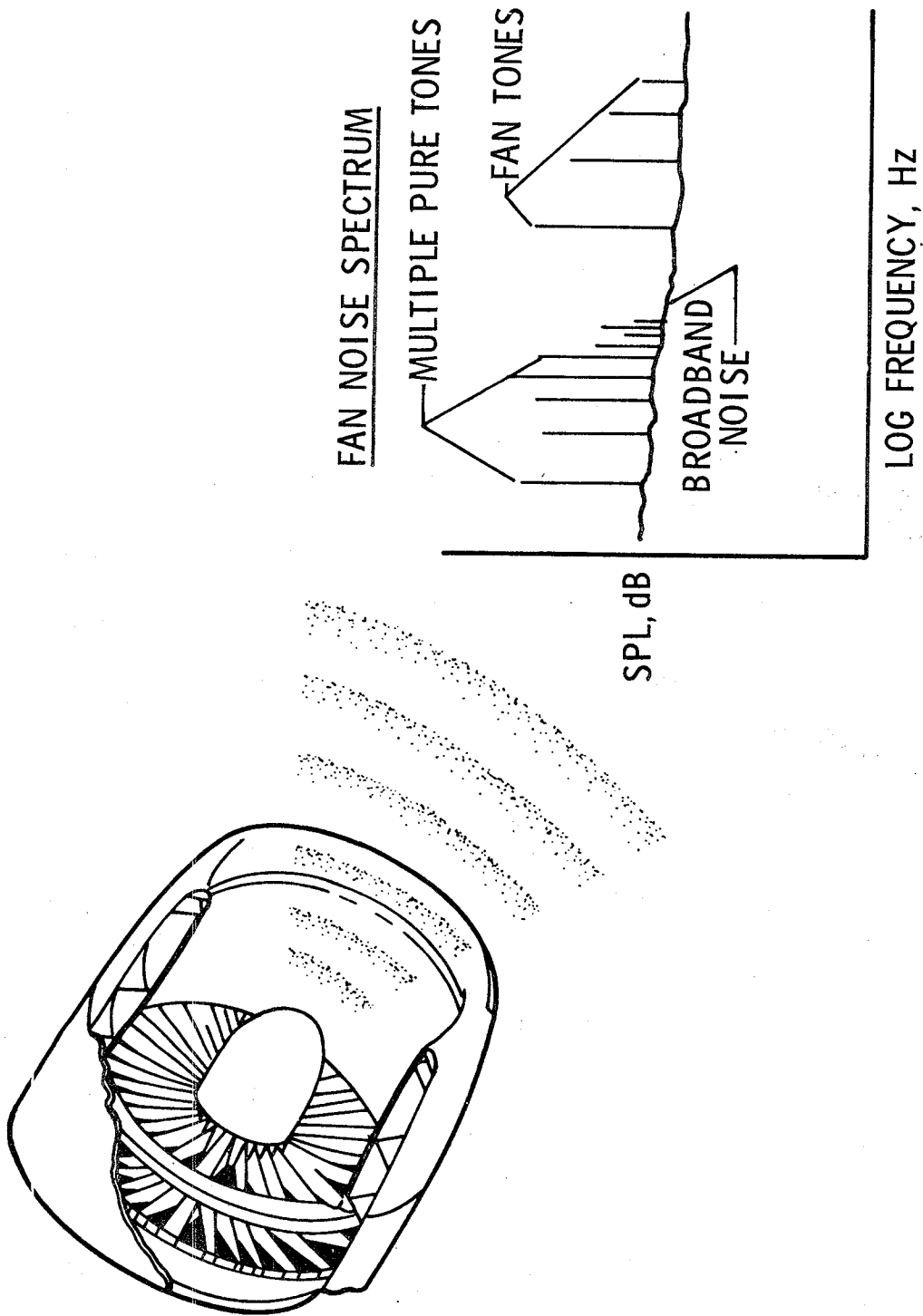


FIGURE 1. - FAN INLET NOISE

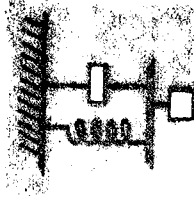
	RANGE OF VALUES			
	ENGINE THRUST CLASS KN	65 - 90	180 - 220	
INLET DIAMETER m		1.0 - 1.4	2.1 - 2.5	
LENGTH/DIAMETER		.7 - 1.0	.6 - .7	
		TAKE OFF	APPROACH	TAKE OFF APPROACH
INLET MACH NUMBER		.3 - .4	.2 - .3	.3 - .4 .2 - .3
MASS FLOW RATE kg/sec		135 - 230	90 - 180	590 - 730 450 - 550
FAN TIP MACH NUMBER		1.2 - 1.3	.9 - 1.1	1.2 - 1.3 .9 - 1.0

FIGURE 2. - INLET DIMENSIONS AND OPERATING CONDITIONS

LIGHT WEIGHT



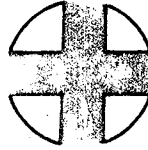
MECHANICAL SIMPLICITY



RETAIN PERFORMANCE



SAFE AND RELIABLE



MINIMUM MAINTENANCE



FIGURE 3. CONSTRAINTS ON INLET NOISE REDUCTION TECHNIQUES.

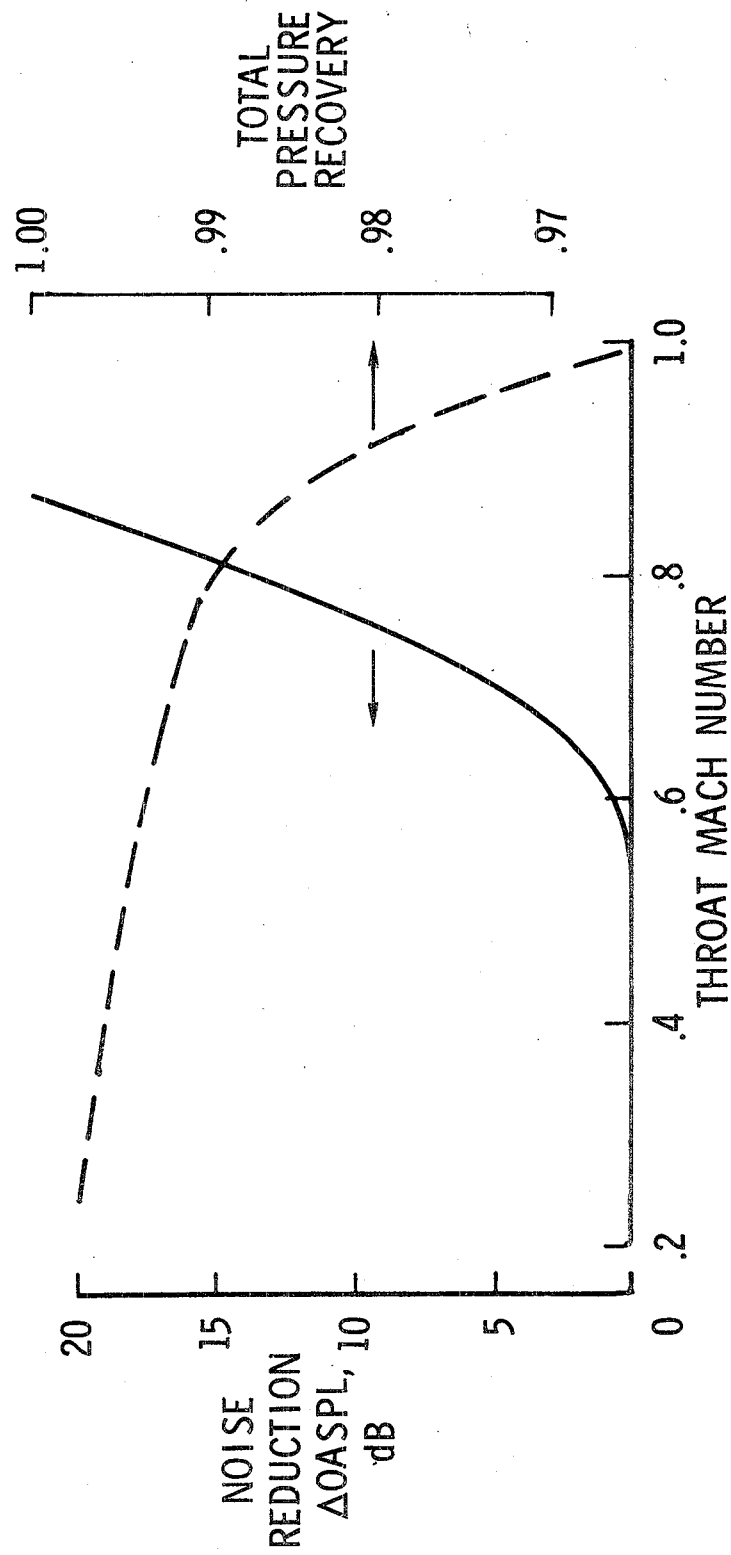


FIGURE 4. - EXAMPLE INLET ACOUSTIC AND AERODYNAMIC PERFORMANCE FOR ZERO FORWARD SPEED.

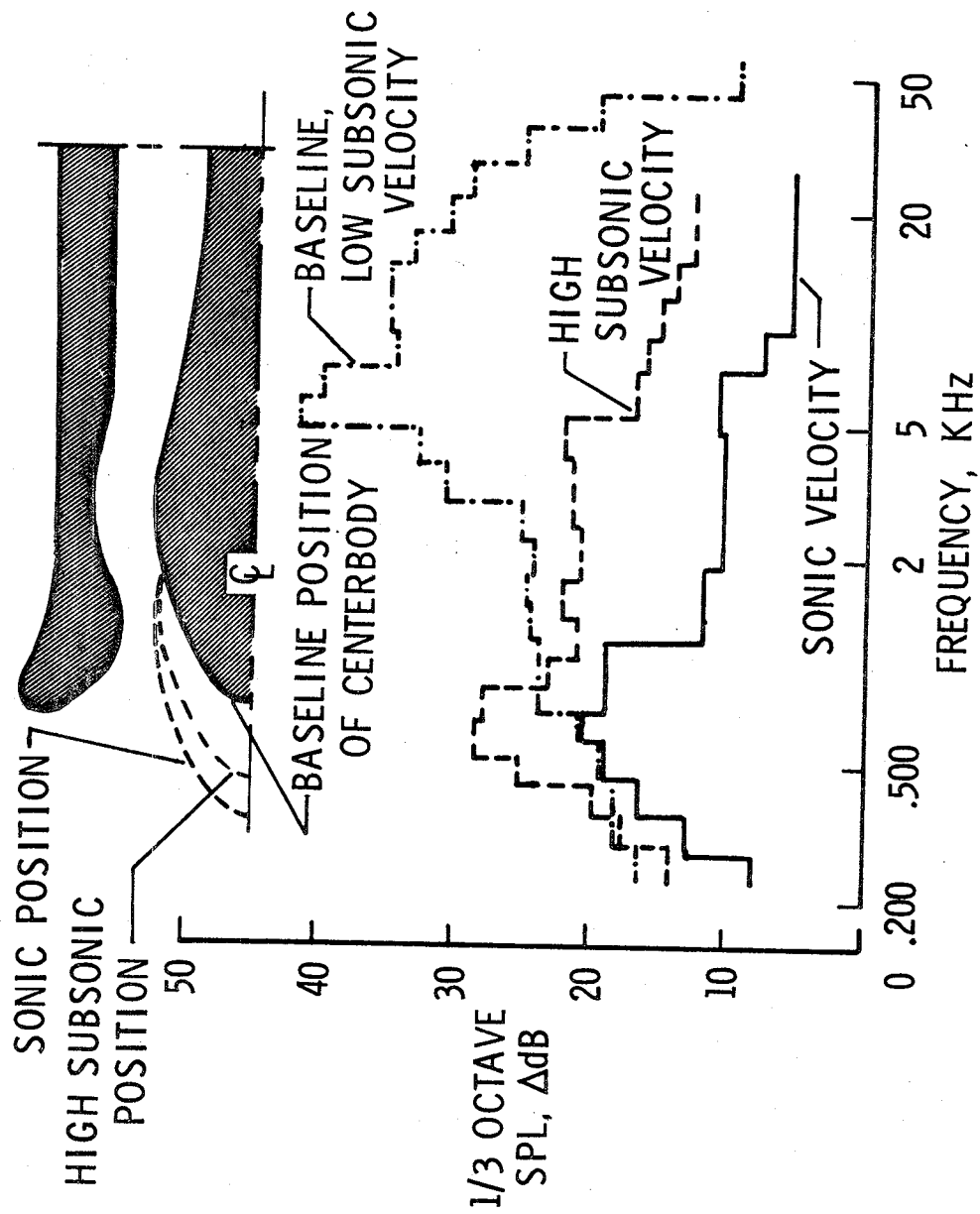


FIGURE 5. - EXAMPLE NOISE SPECTRA FOR SEVERAL INLET THROAT VELOCITIES.

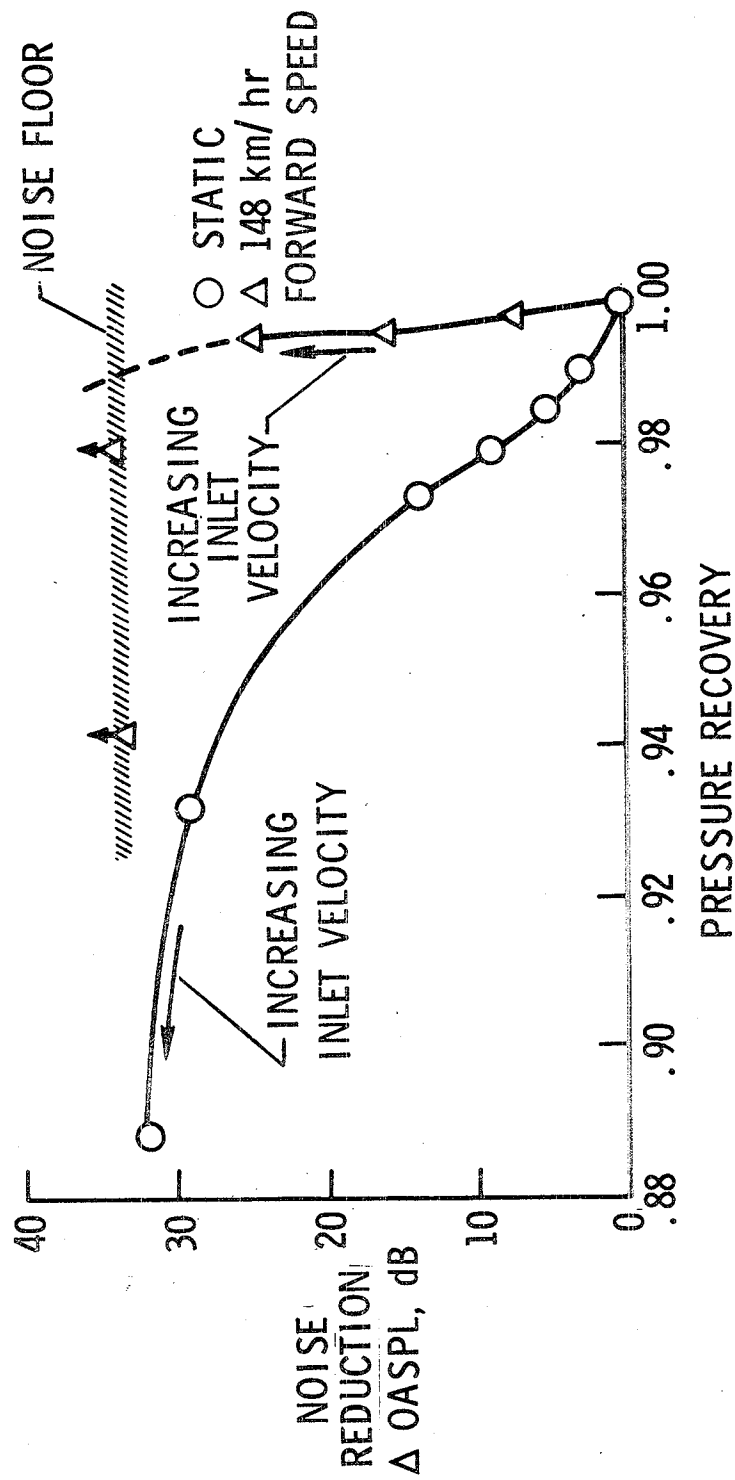


FIGURE 6. - EFFECTS OF FORWARD SPEED ON SONIC INLET NOISE REDUCTION AND COMPRESSOR PRESSURE RECOVERY.

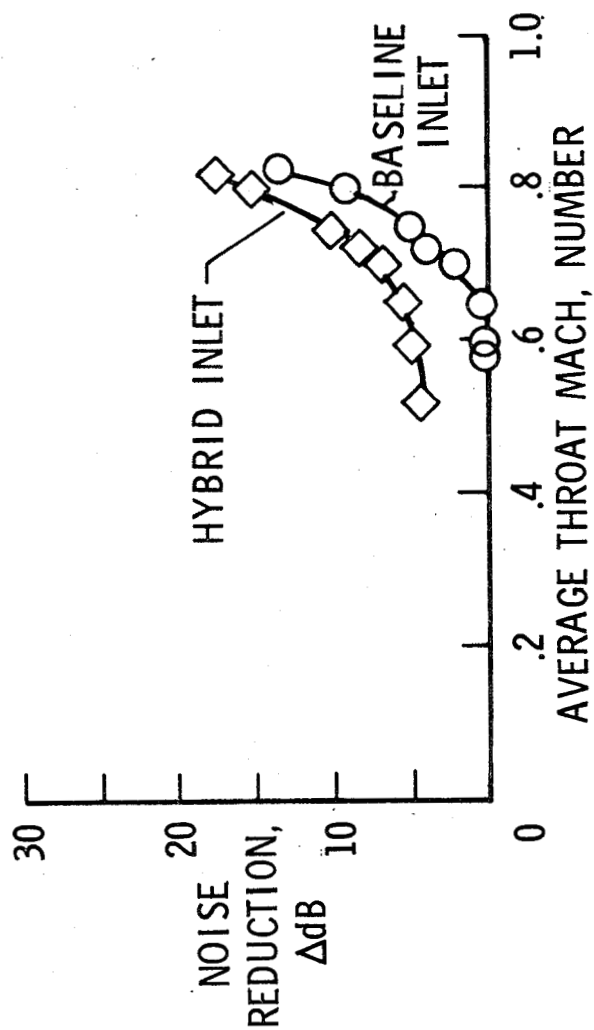
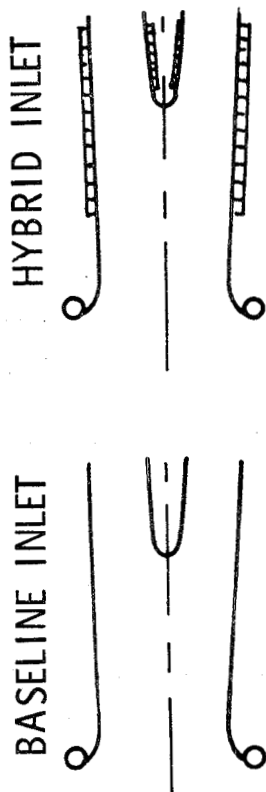


FIGURE 7. - HYBRID INLET ACOUSTIC PERFORMANCE.

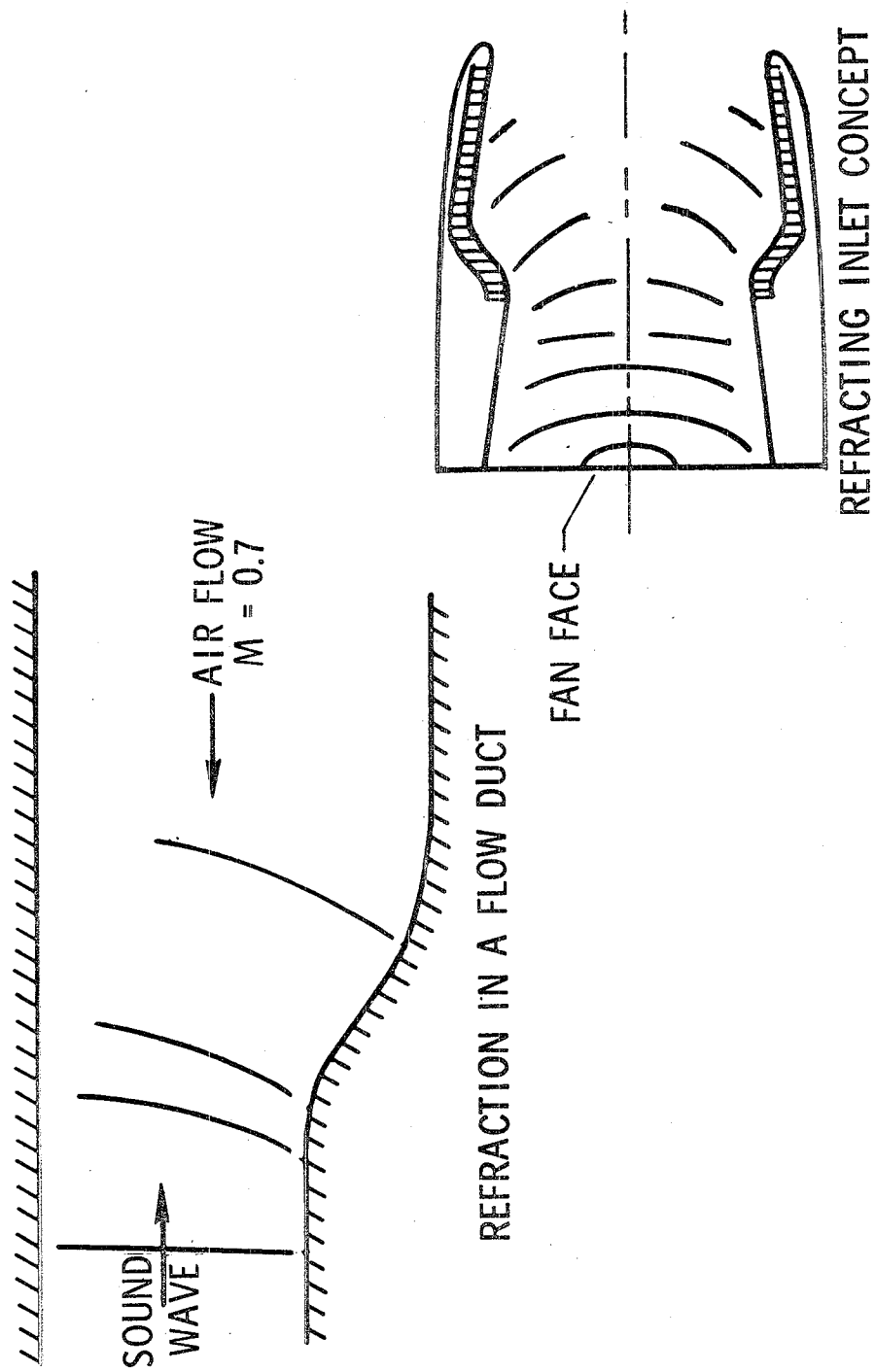
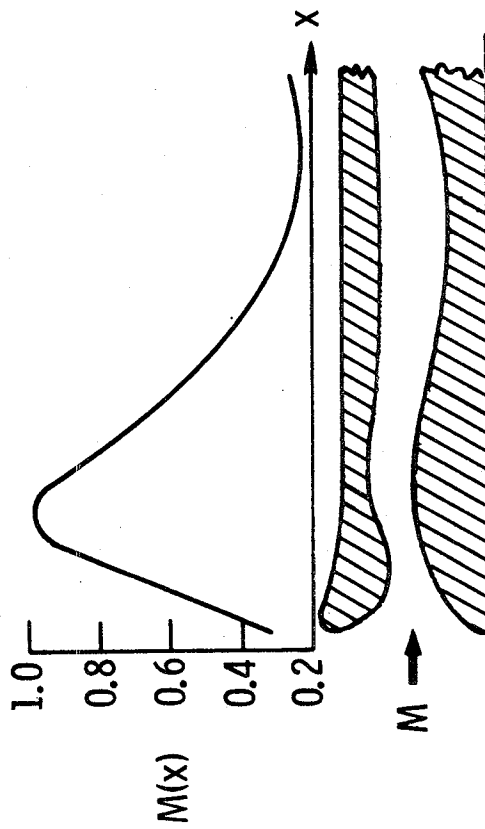


FIGURE 8. - WAVE REFRACTION BY VELOCITY GRADIENTS.

AXIAL MACH NUMBER VARIATION



WAVE EQUATION GOVERNING SOUND FIELD

$$\underbrace{(1-M^2) \frac{\partial^2 \psi}{\partial x^2} - 2 \frac{M}{a} \frac{\partial^2 \psi}{\partial x \partial t} - \frac{1}{2} \frac{\partial^2 \psi}{\partial t^2}}_{\text{WAVE PROPAGATION}} = \underbrace{\left[f_1(M) \frac{\partial \psi}{\partial x} + f_2(M) \frac{\partial \psi}{\partial t} \right] \frac{\partial M}{\partial x}}_{\text{AREA VARIATIONS}} + \underbrace{f_3(M) \frac{\partial \psi}{\partial x} + \frac{\partial^2 \psi}{\partial x^2}}_{\text{NONLINEARITIES}}$$

FIGURE 9. - ONE DIMENSIONAL SOUND PROPAGATION IN HIGH MACH NUMBER INLETS.

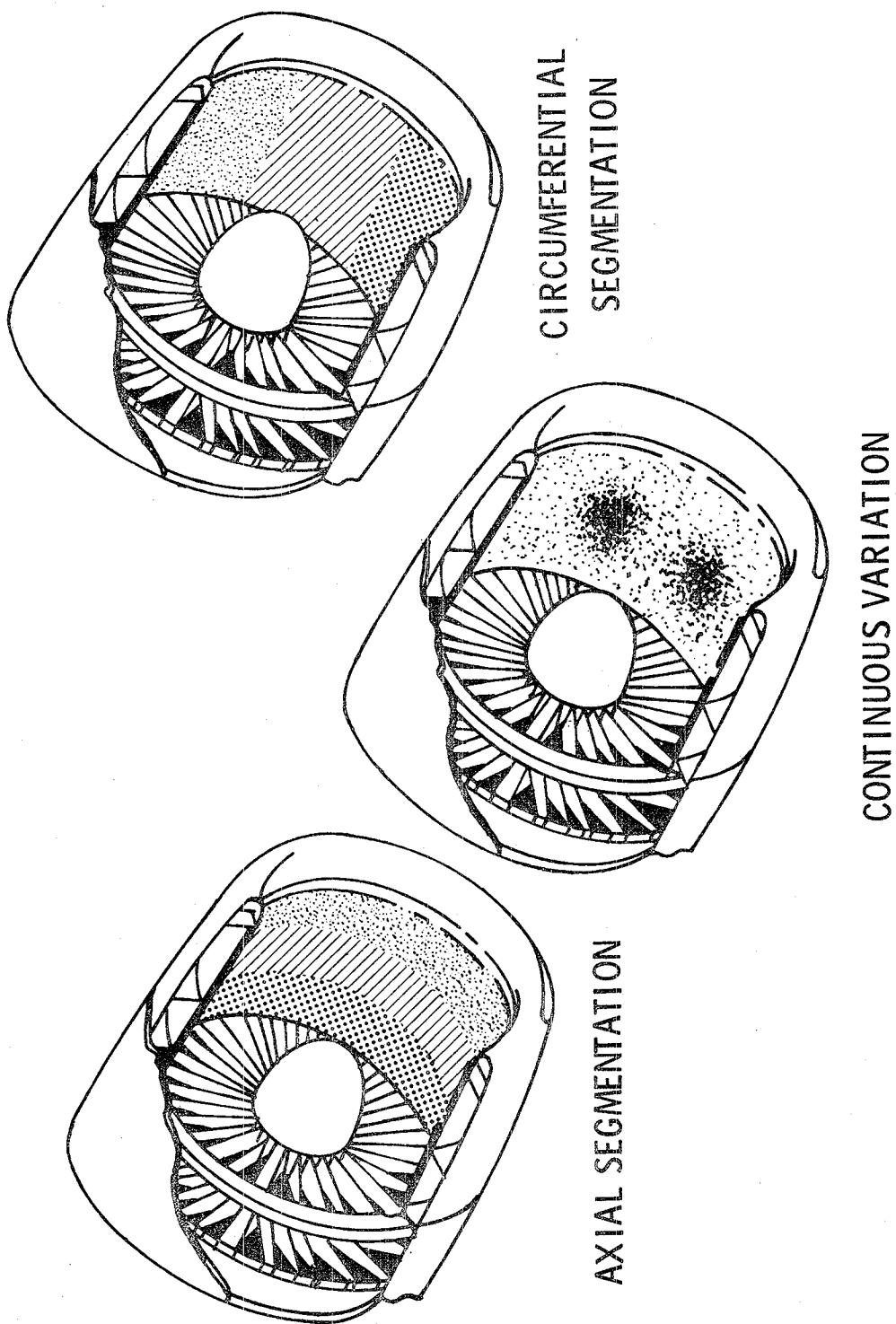


FIGURE 10. VARIABLE IMPEDANCE LINER CONCEPTS.

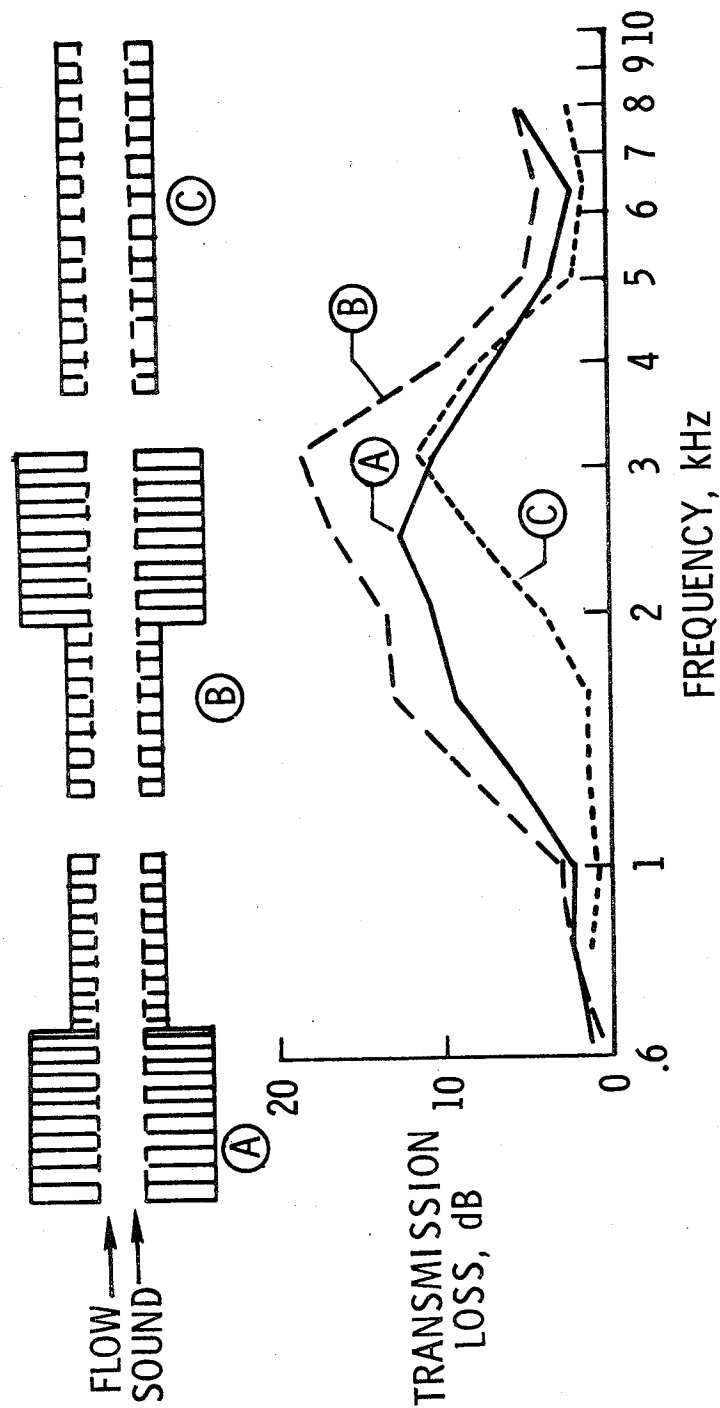


FIGURE 11. - ATTENUATION CHARACTERISTICS OF UNIFORM AND SEGMENTED LINERS.
(FLOW DUCT DATA)

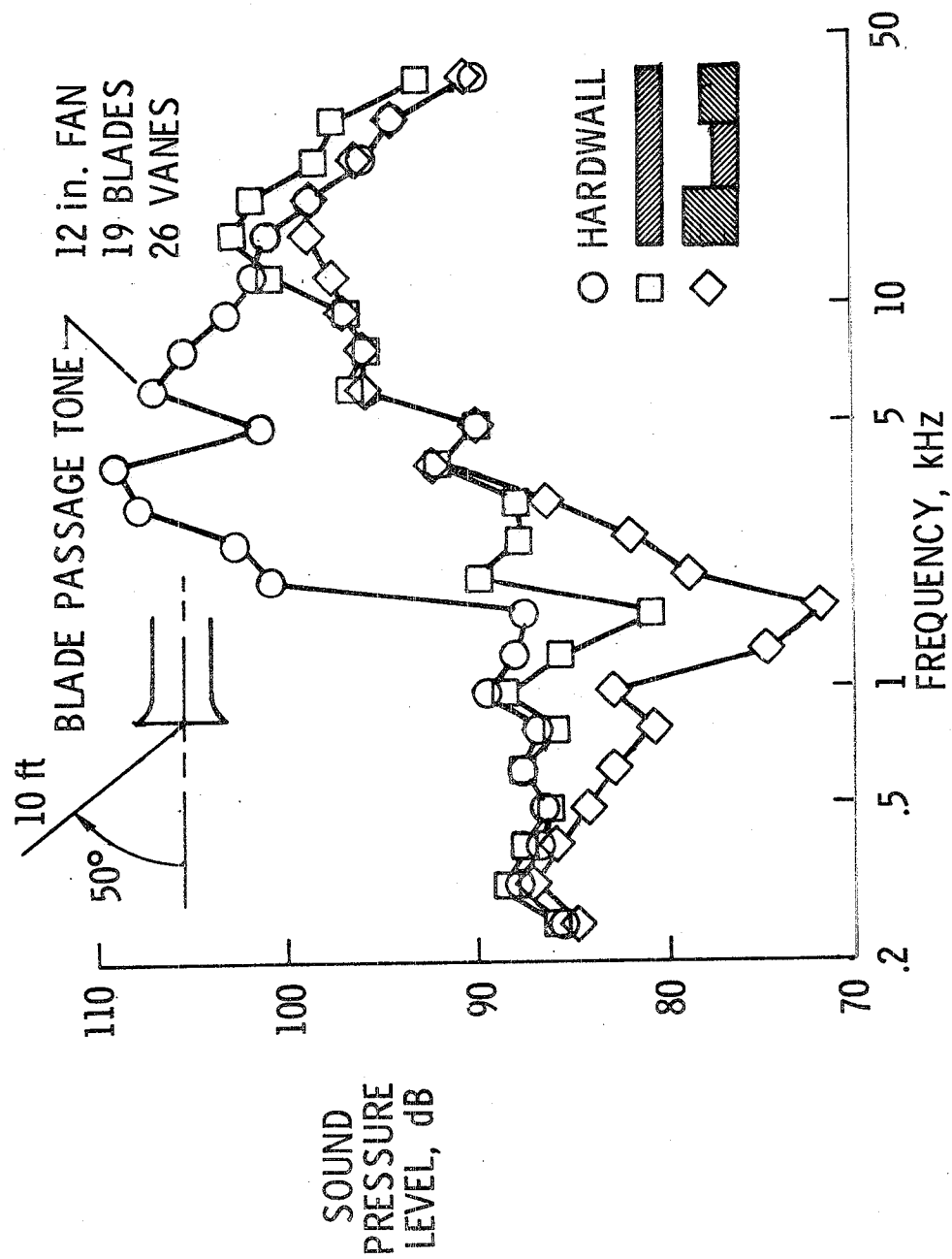


FIGURE 12. - ATTENUATION CHARACTERISTICS OF UNIFORM AND SEGMENTED LINERS.
(FAN DATA)

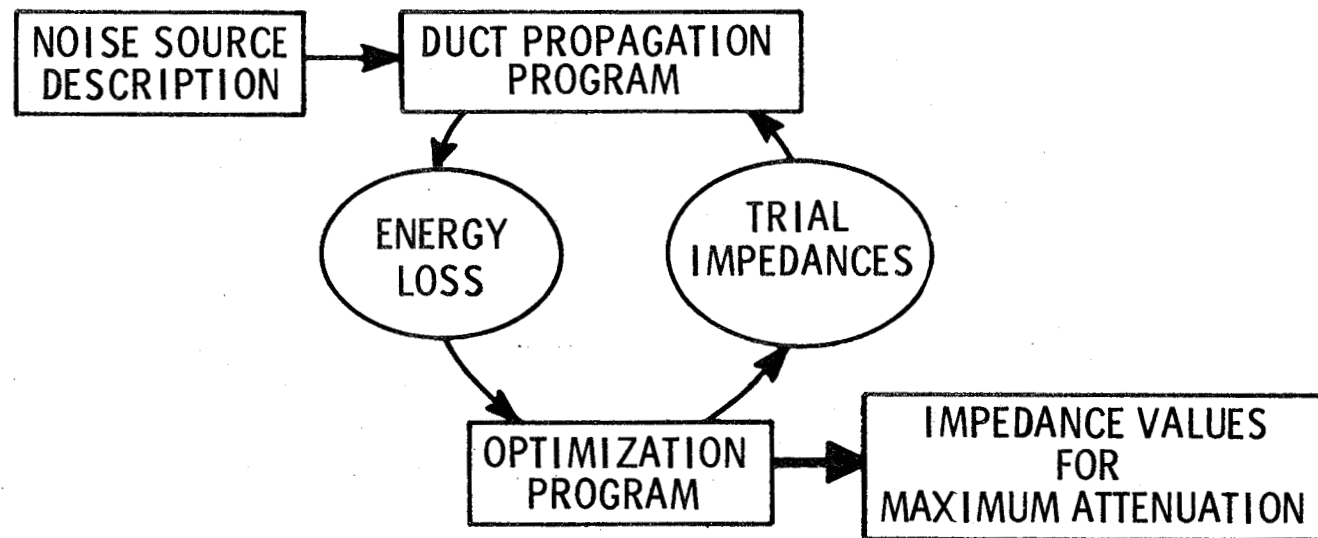
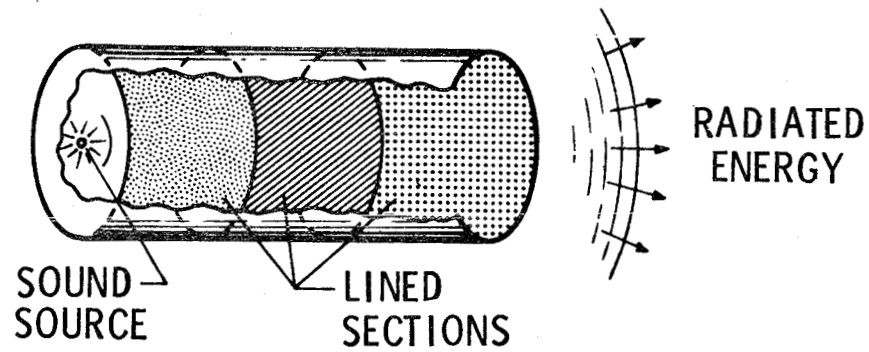


FIGURE 13. - A MULTISEGMENT LINER OPTIMIZATION PROCEDURE.

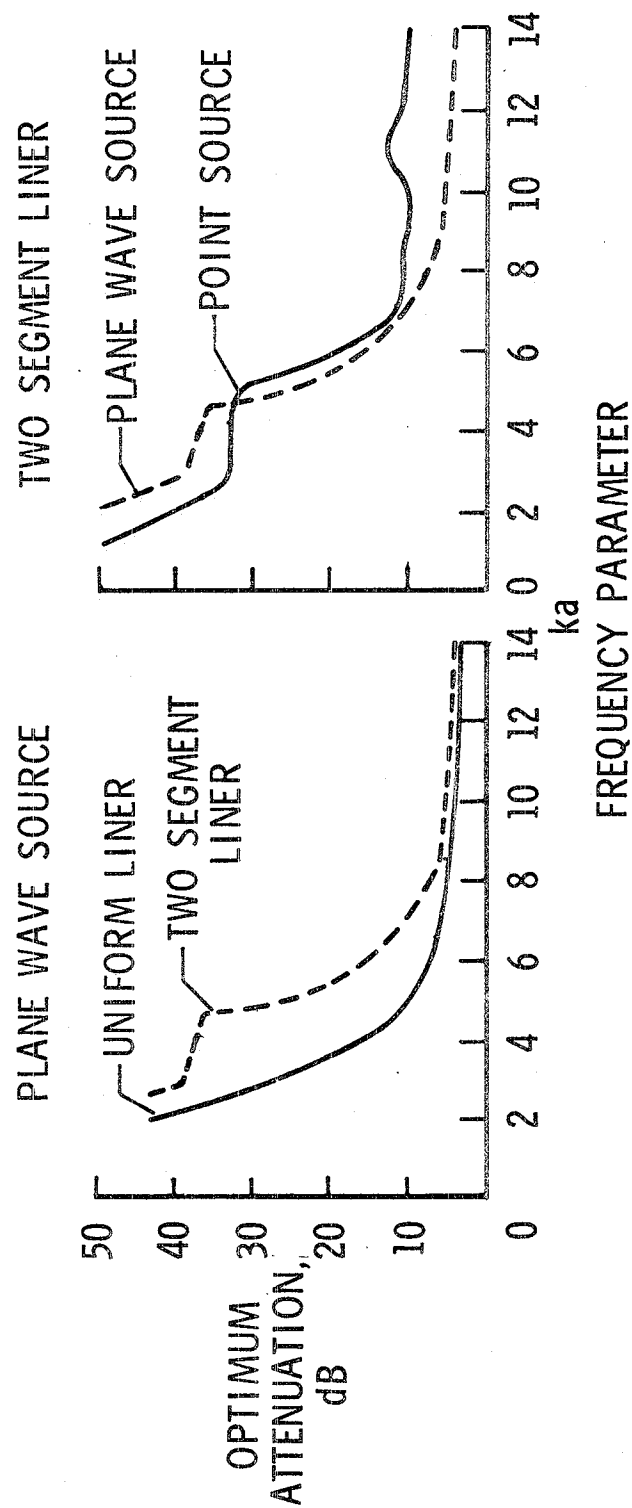
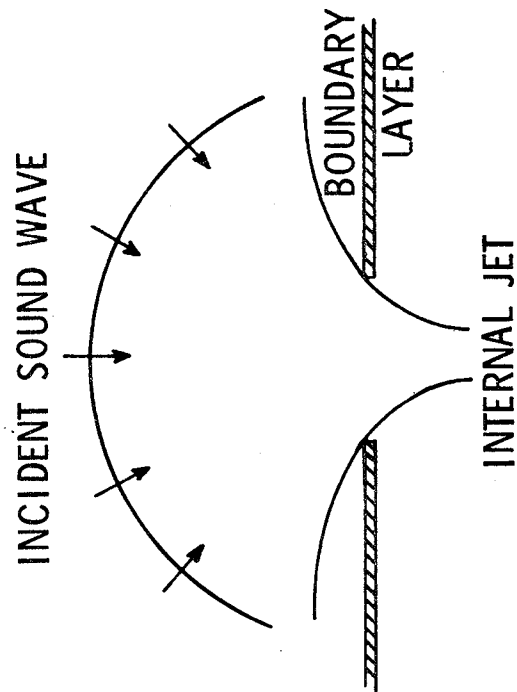


FIGURE 14. - CALCULATED ATTENUATION OF OPTIMAL LINERS FOR A CIRCULAR DUCT.

FLUID MECHANICAL MODEL
OF ORFICE IMPEDANCE



ACOUSTIC MODEL
OF LINER IMPEDANCE

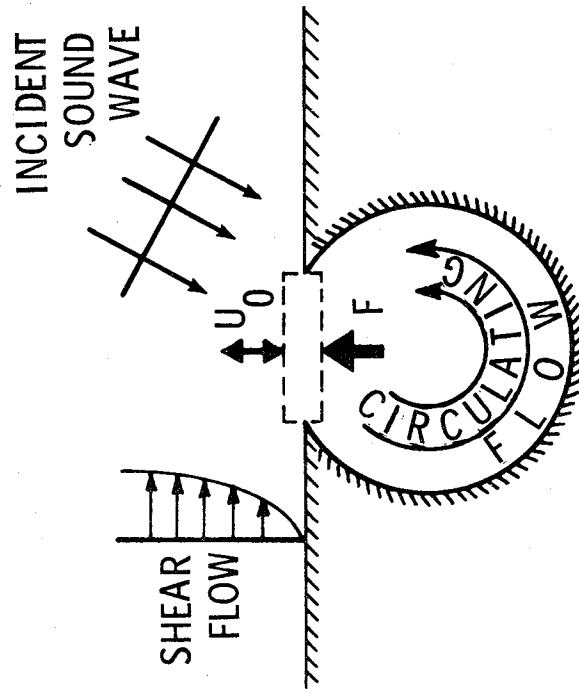
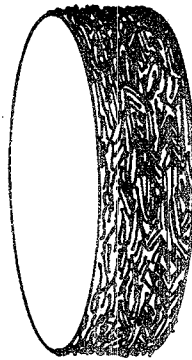
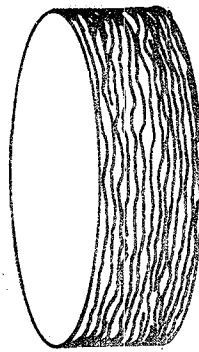


FIGURE 15. - MODELS FOR THE IMPEDANCE OF PERFORATES.

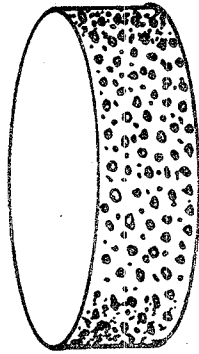
MATERIAL TYPES



FIBROUS



LAYERED



CELLULAR

SOUND-LINER INTERACTION

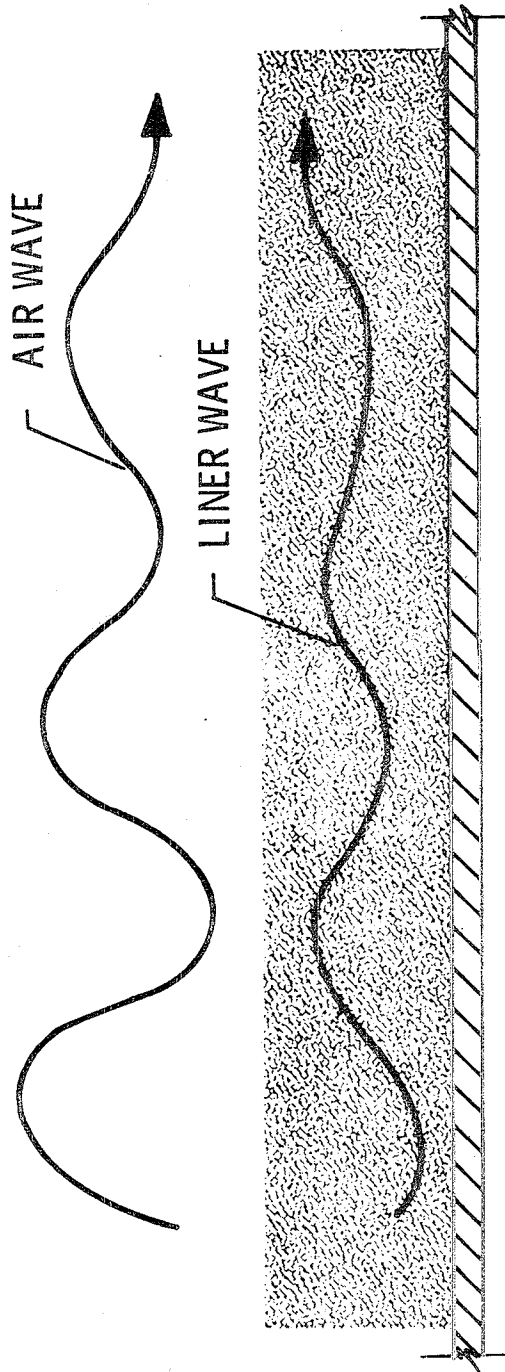
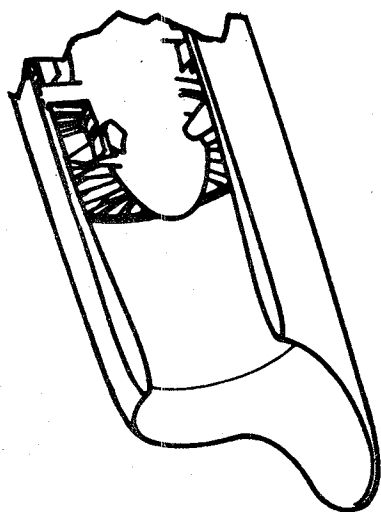


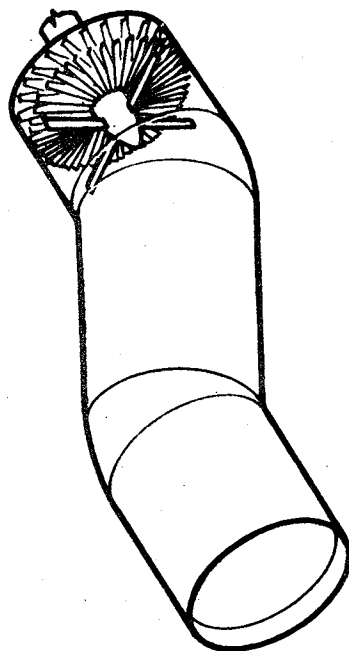
FIGURE 16. - BULK LINERS.



SCARFED INLET

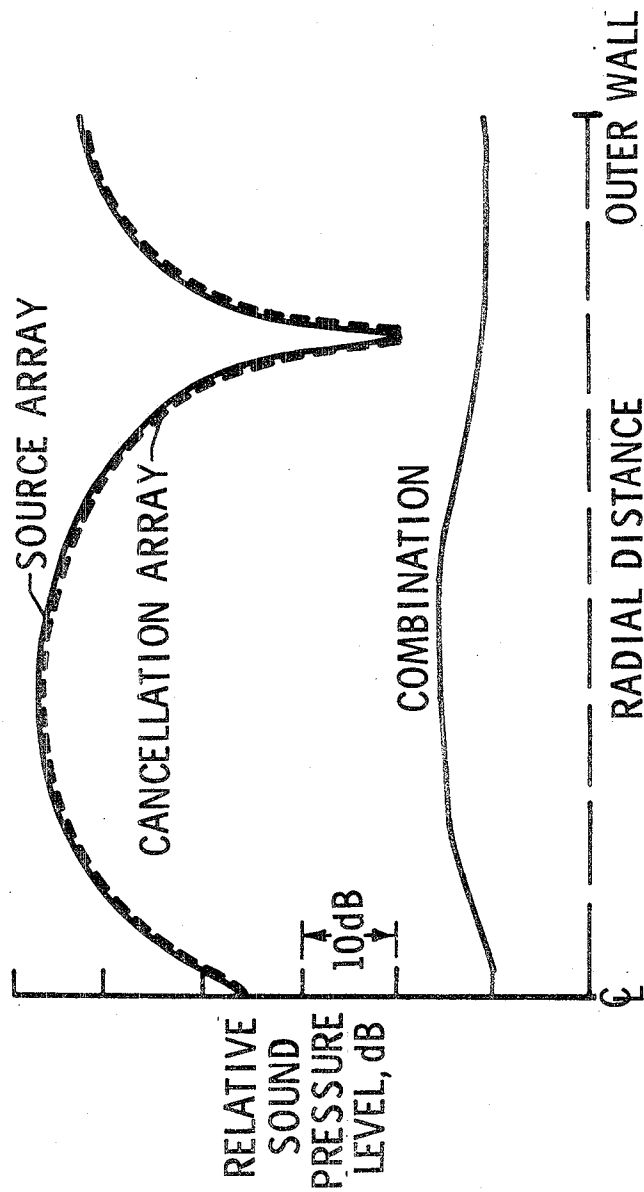
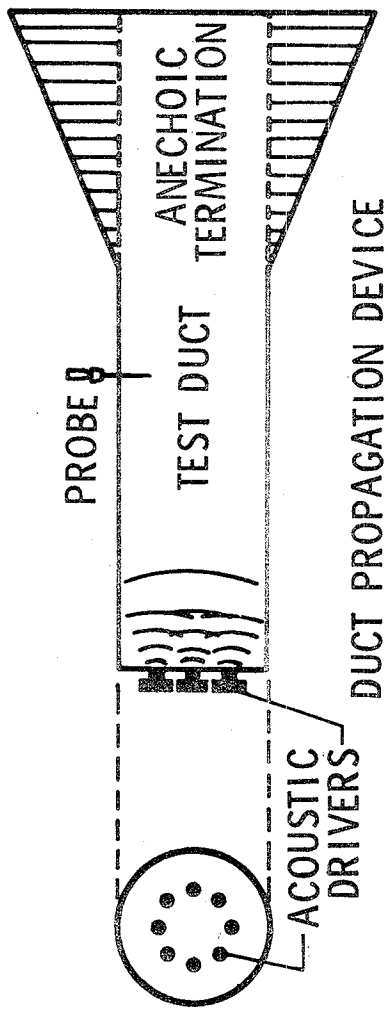


TAPERED INLET



CURVED DUCT

FIGURE 17. - INLET NOISE REDUCTION BY GEOMETRIC SHAPING.



PHASED CANCELLATION OF A CIRCUMFERENTIAL MODE AT 1250 HZ

FIGURE 18. - IN-DUCT SOUND CANCELLATION.

DROPLET CLOUD
IN INLET

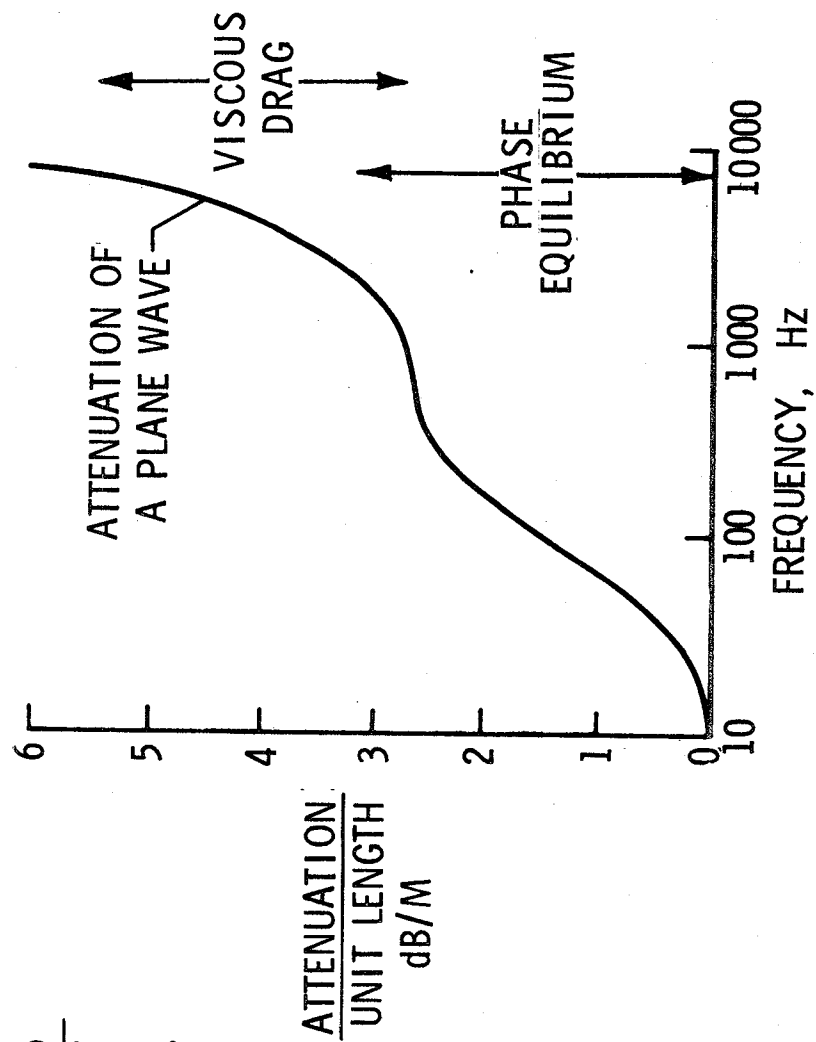
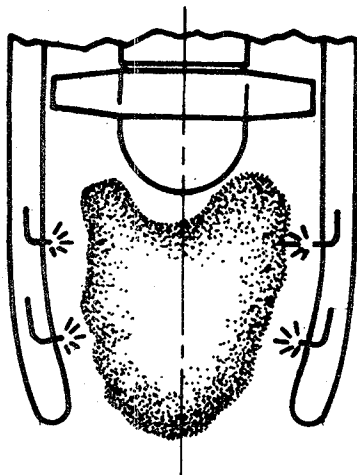


FIGURE 19. - SOUND ATTENUATION BY VAPORIZATION OF LIQUID DROPLETS.

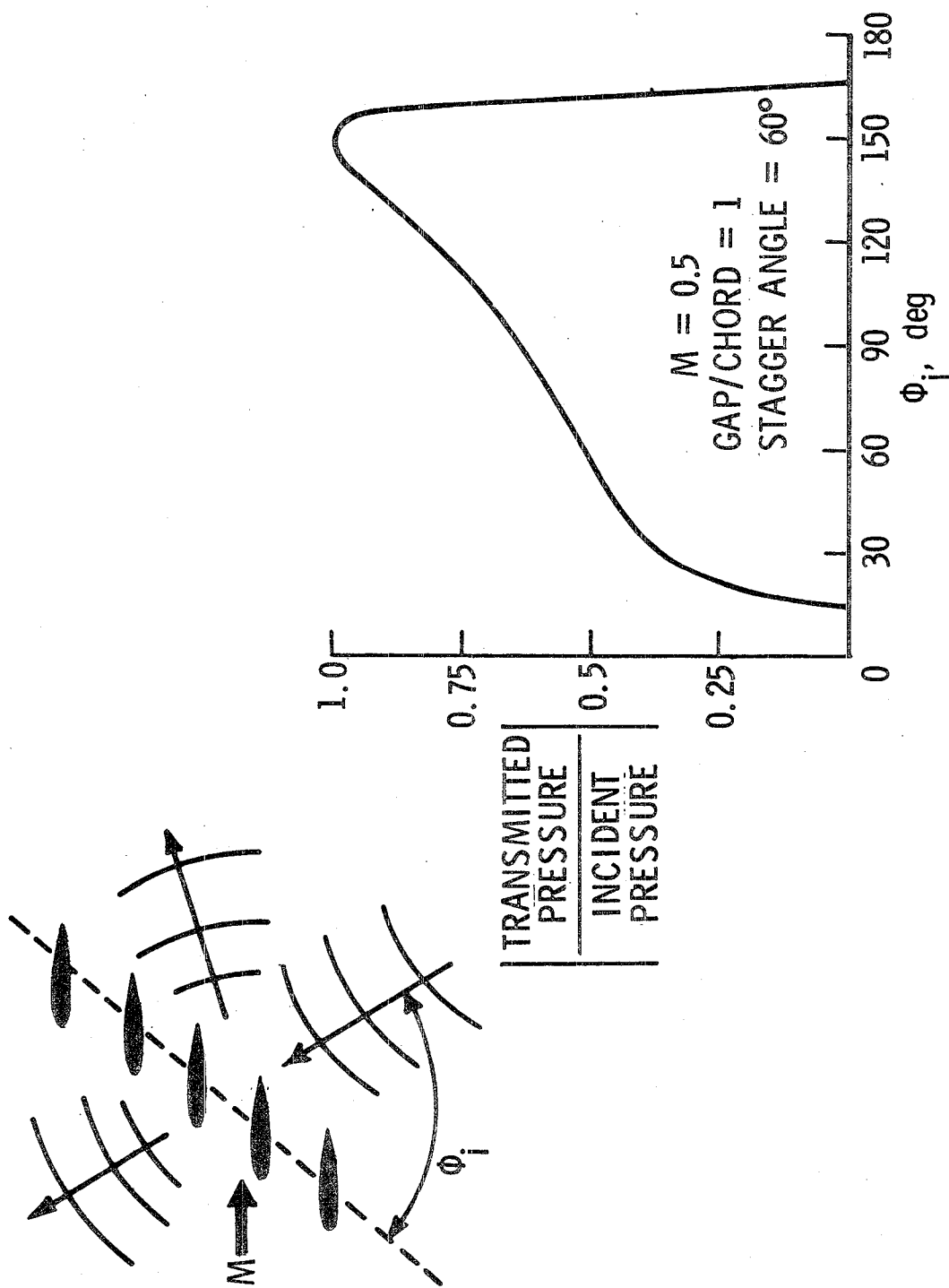


FIGURE 20. - NOISE TRANSMISSION THROUGH A BLADE ROW.